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Contributions to the Mineral Chemistry of Hawaiian Rocks. V. Composition and Origin of Ultramafic Nodules and Megacrysts in a Rhyodacite from Oahu, Hawaiian Islands[1]

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ABSTRACT: Dunite nodules (Fo_{85}) and megacrysts of olivine (Fo_{83-84}) and clinopyroxene ($Fs_{13}Wo_{43}En_{44}$) are present as rare inclusions in the rhyodacite ($\sim$66wt% SiO_2) of Kauaopuu Ridge, Oahu, Hawaii. The rhyodacite is interbedded with caldera-filling tholeiitic lavas of the Waianae volcano. Results: (1) Dunite nodules ($\leq$1 cm) consist of xenomorphic-granular olivine and minor chrome spinel and clinopyroxene ($Fs_6Wo_{47}En_{47}$); olivine ($\sim Fo_{85}$) reacted with the rhyodacite magma to form amphibole and an Fe-enriched margin ($\sim Fo_{80}$). (2) Olivine megacrysts (2–6 mm) contain chrome spinel and melt inclusions; they are resorbed and rarely are slightly enriched in Fe at the margins. (3) Clinopyroxene megacrysts (0.5–1.2 cm) contain ilmenite, ferropseudobrookite, and melt inclusions; they are slightly resorbed and enriched in MgO at unresorbed margins. Conclusions: (1) Olivine from the dunite and olivine megacrysts compositionally resemble olivine in typical dunite inclusions in alkalic olivine basalts of Hawaii, as well as olivine phenocrysts in basalts of Hawaii. Clinopyroxene in the dunite resembles that in typical dunite inclusions of Hawaii, whereas clinopyroxene megacrysts are like phenocrysts in basalts of Hawaii. (2) The reaction relationship between the dunite and the rhyodacite magma suggests that the nodules are accidental. A positive gravity anomaly over Waianae volcano indicates a dense, perhaps olivine-rich zone beneath the volcano—a possible source for the nodules. (3) The resorption of the megacrysts and their compositions indicate that they are probably remnant phenocrysts of basaltic magma from which the rhyodacite formed by igneous differentiation. (4) Rhyodacite magma was derived from a basaltic parent and it later incorporated dunite fragments, probably during ascent.

MAFIC AND ULTRAMAFIC inclusions in the volcanic rocks of Hawaii have been studied by White (1966), Jackson (1968), Kuno (1969), Jackson and Wright (1970), and Beeson and Jackson (1970). Most inclusions occur in basaltic rocks (mainly of the alkalic and nephelinic suites) and some are in more highly differentiated rocks such as hawaiite and trachyte (Jackson 1968). Only rarely have inclusions been found in rocks of the tholeiitic suite (Powers 1955: 90, White 1966) and none have been previously observed in rhyodacite, a rock interpreted as the most highly differentiated member of the tholeiitic suite (Macdonald and Katsura 1962, 1964; Bauer et al. 1973).

Here, rare nodules of dunite and mega-

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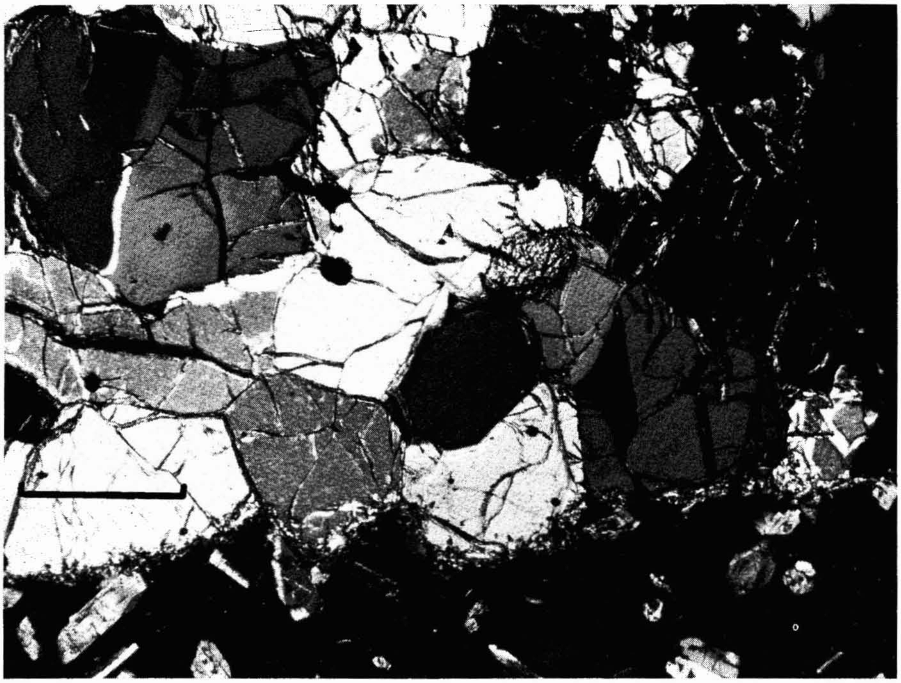

FIGURE 1. Texture of a dunite nodule in rhyodacite of Kauaopuu Ridge, Oahu, Hawaiian Islands. Note triple-point junctures between some olivine grains, indicating recrystallization. A fine-grained discontinuous rim of amphibole is present between the margin of the nodule and the glass of the rhyodacite host (black area, bottom). Crossed nicols. Scale bar equals 0.5 mm.

crysts of olivine and clinopyroxene from near the base of the rhyodacite lava flow at Kauaopuu Ridge, Oahu, Hawaiian Islands, were studied by microscopic and microprobe techniques (Keil, Fodor, and Bunch 1972; Bauer et al. 1973). Such inclusions in a host rock of ~ 66 wt % SiO_2 pose some interesting questions—for example, whether the rhyodacite was at one time in contact with mantle material (accidental inclusions) or whether the inclusions are of high-pressure cognate origin, thus providing an estimation of minimum depth of formation for the rhyodacite.

HOST ROCK

The rhyodacite occurs on the western end of Oahu, Hawaiian Islands, about 35 miles west of Honolulu (Bauer et al. 1973). The flow on Kauaopuu Ridge ranges in thickness from 15 to 70 m and also makes up the neighboring Mauna Kuwale Ridge to the south. It belongs to the middle member of the Waianae Volcanic Series (Macdonald 1949) and is interbedded with caldera-filling tholeiitic lavas of the Waianae volcano (Macdonald and Abbott 1970:359).

The rhyodacite from Kauaopuu Ridge is composed mainly of glassy matrix (70–75 volume %), about 12-percent plagioclase (An_{25}), 7-percent amphibole, 3-percent biotite, 1-percent oxides, and a trace of orthopyroxene (Bauer et al. 1973). The Mauna Kuwale rhyodacite was described by Stearns and Vaksvik (1935) and Macdonald (1940) and is very similar to that of Kauaopuu Ridge (same flow; Bauer et al. 1973). Because of its association with the tholeiitic basalts and its low alkali content relative to trachytes, the rhyodacite is considered to be the most highly differentiated member of the tholeiitic volcanic suite (Macdonald and Katsura 1962, 1964; Bauer et al. 1973).

TABLE 1

RESULTS OF ELECTRON MICROPROBE ANALYSES OF OLIVINE IN RHYODACITE FROM KAUAOPUU RIDGE, OAHU, HAWAIIAN ISLANDS

COMPOUND	OLIVINE IN DUNITE NODULE	FE-ENRICHED RIM OF NODULE	OLIVINE IN DUNITE NODULE	FE-ENRICHED RIM OF NODULE	OLIVINE MEGACRYSTS			RIM OF ONE MEGACRYST IN RHYODACITE
SiO_2	40.00	39.2	40.2	39.4	40.0	39.8	40.2	
Cr_2O_3	0.01	<0.01	<0.01	<0.01	0.02	0.02	0.02	
FeO	15.1	19.6	14.7	18.3	15.6	16.5	14.8	16.0
MnO	0.19	0.68	0.20	0.62	0.27	0.27	0.26	
MgO	44.9	41.2	45.5	42.3	44.5	43.7	45.2	44.2
CaO	0.05	0.11	0.06	0.10	0.12	0.11	0.18	
NiO	0.30	0.23	0.27	<0.01	0.48	0.40	0.32	
TOTAL	100.55	101.02	100.93	100.72	100.99	100.80	100.98	
Fo	84.1	78.9	84.7	80.5	83.6	82.5	84.5	83.1
Fa	15.9	21.1	15.3	19.5	16.4	17.5	15.5	16.9

NOTE: Numerals represent weight percent.

INCLUSIONS

The inclusions in the Kauaopuu rhyodacite consist of dunite nodules, ranging from fresh to entirely altered nodules (probably deuteric alteration, as indicated by the absence of weathering in the host rock), and of megacrysts of olivine and clinopyroxene.

Dunite

The two examined inclusions of fresh dunite, each about 1 cm in diameter, consist almost entirely of anhedral olivine grains (xenomorphic-granular) in a slightly recrystallized texture, including triple-point junctures (Figure 1). Their texture is metamorphic rather than cumulate. Small amounts of chrome spinel and, in one sample, a few interstitial grains of clinopyroxene were observed. Olivine is nearly constant in composition (Fo_{85}; Table 1) but at the margin (10–15 microns), Fo decreases to $\sim Fo_{80}$ (i.e., iron enrichment). There is also enrichment in MnO and a slight increase in CaO at the margin. These increases in Fe, Mn, and Ca apparently resulted from a reaction between the dunite nodules and the rhyodacite magma. Also indicative of a reaction relationship is a discontinuous ring of amphibole around the dunite (Figure 1). This amphibole has a composition identical to that of the amphibole present as phenocrysts throughout the rhyodacite (Bauer et al. 1973). Analyses of chrome spinel and rare grains of clinopyroxene are listed in Tables 2 and 3.

Olivine Megacrysts

Olivine megacrysts range from 3 to 6 mm in size, but, because they are highly resorbed (Figure 2), their original size was probably larger. There is no noticeable increase in iron content at the margins of two and only a slight increase at the margin of one olivine grain; thus, this olivine differs from that in the dunite nodules. Each grain has near-constant composition; combined, they range from Fo_{85} to Fo_{83} (Table 1). Olivine megacrysts are only slightly richer in FeO, MnO, and CaO than are the dunite olivine (excluding dunite rims). Also, two megacrysts are richer in NiO.

One megacryst has chrome spinel lower in Al_2O_3 and FeO, and higher in Cr_2O_3 than the chrome spinel in the dunite (Table 2). There are also melt inclusions (Table 4) in the olivine ranging from about 10 to 20 microns in size. They contain amphibole, orthopyroxene, and high-SiO_2 (~ 70 wt. %) glass. Amphibole and orthopyroxene in the melt inclusions are compositionally similar to those present as phenocrysts in the host.

Clinopyroxene Megacrysts

The two clinopyroxene megacrysts studied are 1 cm and 6 mm in size, respectively. One

TABLE 2

RESULTS OF ELECTRON MICROPROBE ANALYSES OF THE RHYODACITE FROM KAUAOPUU RIDGE, OAHU, HAWAIIAN ISLANDS

COMPOUND	CHROME SPINEL IN DUNITE NODULE	CHROME SPINEL IN OLIVINE MEGACRYST	ILMENITE IN CLINO-PYROXENE MEGACRYST	FERROPSEUDOBROOKITE IN CLINOPYROXENE MEGACRYST
SiO_2	0.45 (0.32– 0.60)	0.63	0.51	0.51
TiO_2	2.2 (2.0 – 2.4)	2.4	47.5	60.1
Al_2O_3	11.1 (10.6 –11.6)	6.5	1.1	2.3
V_2O_3	0.29 (0.16– 0.36)	0.16	0.26	0.46
Cr_2O_3	29.5 (26.1 –31.5)	40.9	0.31	0.35
FeO	45.4 (42.6 –47.8)	38.8	41.8	28.1
MnO	0.31 (0.25– 0.40)	0.43	0.47	0.10
MgO	6.9 (6.5 – 7.3)	6.0	7.2	7.3
CaO	0.03 (<0.01– 0.10)	0.08	0.42	0.46
ZnO	0.14 (<0.01– 0.46)	0.33	0.12	<0.01
NiO	0.29 (0.22– 0.48)	0.38	–	–
SUM	96.61	96.61	99.69	99.68
		Recalculated Data		
FeO	23.9	24.2	29.2	7.4
Fe_2O_3	23.9	16.2	13.9	23.0
TOTAL	99.01	98.21	100.99	101.98

NOTE: Numerals represent weight percent. Numerals in parentheses represent ranges.

TABLE 3

RESULTS OF ELECTRON MICROPROBE ANALYSES OF THE RHYODACITE FROM KAUAOPUU RIDGE, OAHU, HAWAIIAN ISLANDS

COMPOUND	CLINOPYROXENE IN DUNITE NODULE	CLINOPYROXENE MEGACRYST	MG-RICH RIM	CLINOPYROXENE MEGACRYST	MG-RICH RIM
SiO_2	53.7	52.2	(54.2 – 50.5)	52.5	(53.7 – 50.6)
TiO_2	0.36	1.2	(0.71– 1.4)	1.1	(0.69– 1.3)
Al_2O_3	2.1	2.8	(1.7 – 3.3)	2.6	(2.0 – 3.2)
Cr_2O_3	0.39	0.08	(0.19–<0.01)	<0.01	(0.03–<0.01)
FeO	4.0	7.6	(6.7 – 8.2)	8.3	(6.6 – 9.5)
MnO	0.09	0.18	(0.10– 0.25)	0.23	(0.16– 0.31)
MgO	16.6	15.5	(16.3 – 15.0)	15.2	(16.9 – 14.6)
CaO	23.4	21.0	(21.3 – 20.4)	20.7	(21.5 – 20.0)
Na_2O	0.41	0.37	(0.29– 0.42)	0.42	(0.24– 0.55)
TOTAL	101.05	100.93		101.05	
Fs	6.3	12.2		13.4	
En	46.5	44.5		43.8	
Wo	47.2	43.3		42.8	

NOTE: Numerals represent weight percent. Numerals in parentheses represent ranges.

clinopyroxene is highly resorbed and each is nearly constant in composition (Table 3). However, at the unresorbed margins of each grain is a rim enriched in Mg and depleted in Fe (Figure 3). Compared to clinopyroxene in the dunite, the megacrysts are enriched in FeO, TiO_2, Al_2O_3, and MnO, and are depleted in CaO and Cr_2O_3 (Table 3).

One clinopyroxene megacryst contains inclusions of apatite (CaO, 53.9 wt. %; P_2O_5, 39.5 %; Cl, 0.21 %; Y_2O_3, 0.16 %; La_2O_3, 0.07; Ce_2O_3, 0.18 %) and each grain contains melt inclusions and ilmenite crystals. In addition, the largest megacryst contains ferropseudobrookite. Both Ti-phases (Table 2) are high in MgO content.

Near one margin of the largest megacryst is a line of melt inclusions that are 5 to 10

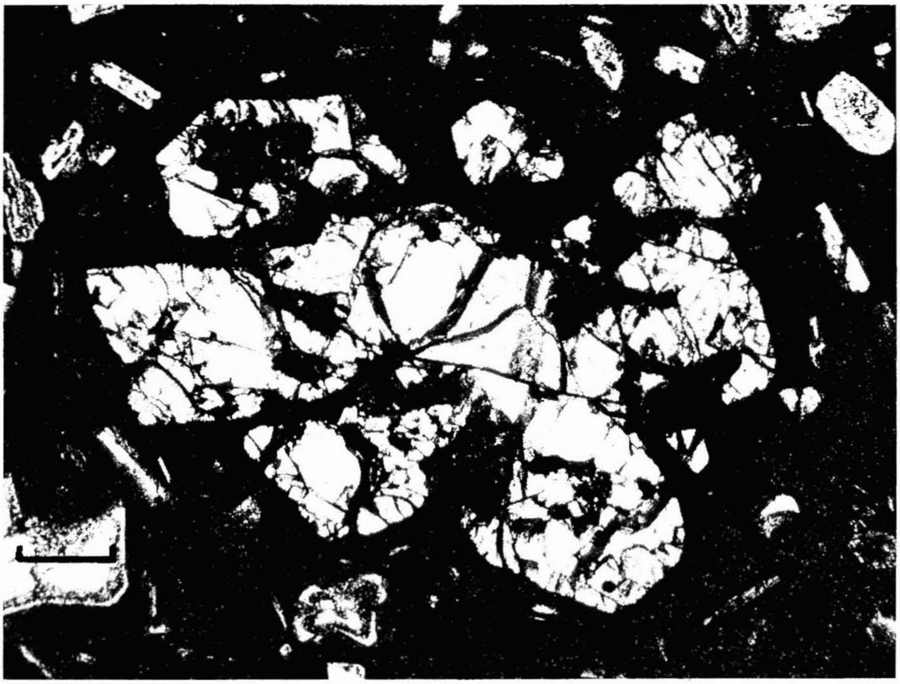

FIGURE 2. Resorbed olivine megacryst in rhyodacite of Kauaopuu Ridge, Oahu, Hawaiian Islands. Plane polarized light. Scale bar equals 0.5 mm.

TABLE 4

RESULTS OF BROAD-BEAM* ELECTRON MICROPROBE ANALYSES OF BULK COMPOSITIONS OF MELT INCLUSIONS IN THE RHYODACITE FROM KAUAOPUU RIDGE, OAHU, HAWAIIAN ISLANDS

COMPOUND	MEGACRYST OF OLIVINE	MEGACRYST OF OLIVINE	MEGACRYST OF CLINOPYROXENE
SiO_2	60.3	59.5	71.1
TiO_2	0.48	0.45	0.16
Al_2O_3	13.1	14.7	14.5
FeO	3.9	4.9	0.35
MnO	0.06	0.06	0.01
MgO	6.7	4.2	0.25
CaO	4.5	4.1	1.4
Na_2O	3.0	3.8	4.6
K_2O	3.9	3.4	3.5
P_2O_5	0.16	0.21	0.33
TOTAL†	96.10	95.32	96.20

NOTE: Numerals represent weight percent.
*Approximately 10 microns.
†Total apparently low because of presence of volatiles not detectable by electron microprobe.

microns in size (Figure 4). These inclusions separate the rim of Mg-enrichment from the remaining part of the pyroxene crystal and have high SiO_2 and alkali contents (Table 4). Adjacent to the megacryst margin is a reaction zone in the host that contains orthopyroxene crystals with the same composition as orthopyroxene elsewhere in the rhyodacite (Figure 4). These orthopyroxene crystals also contain high-SiO_2 melt inclusions.

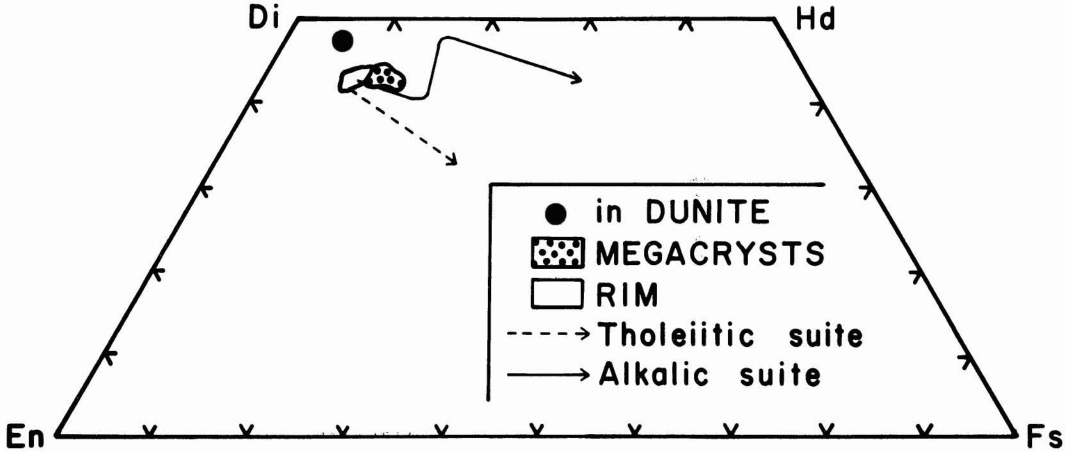

FIGURE 3. Pyroxene quadrilateral diagram illustrating the compositions of pyroxene in dunite and pyroxene megacrysts and their rims, in rhyodacite of Kauaopuu Ridge, Oahu, Hawaiian Islands. Fractionation trends are for the tholeiitic and alkalic suites of Maui, Hawaiian Islands (Fodor, Keil, and Bunch 1975).

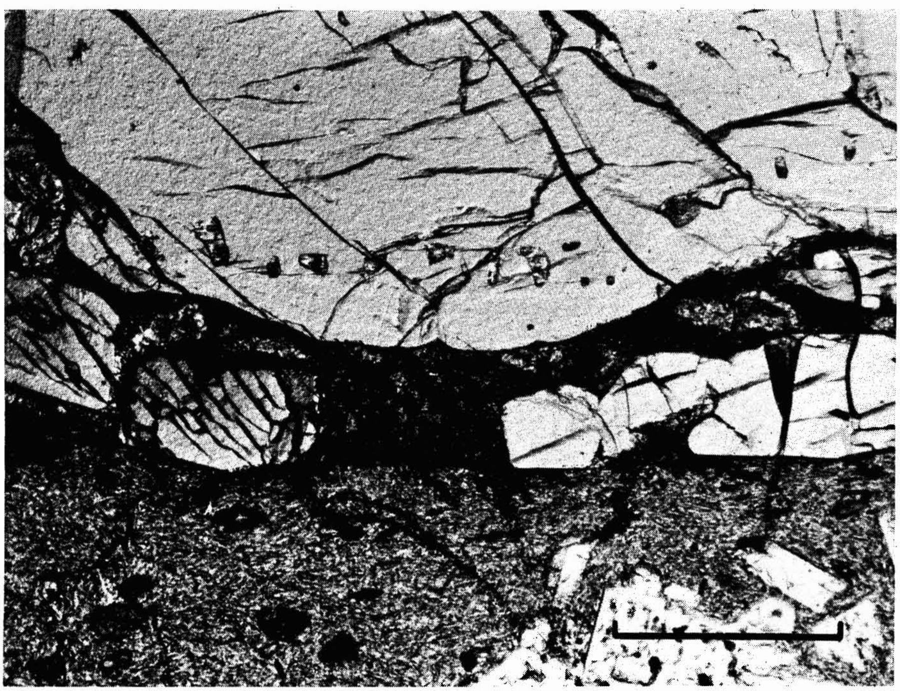

FIGURE 4. Margin of a clinopyroxene megacryst with a line of melt inclusions, an Mg-enriched margin (lighter color in pyroxene below line of melt inclusions), and a reaction zone with the rhyodacite containing orthopyroxene crystals. Plane polarized light. Scale bar equals 0.5 mm.

DISCUSSION

Source of the Dunite Nodules

When comparing compositions of olivine in the dunite nodules to those of olivine in lherzolite inclusions of Hawaii (White 1966), to true dunite inclusions in alkalic olivine basalt of Hawaii (White 1966), and to olivine phenocrysts of olivine basalt of Hawaii (Fodor, Keil, and Bunch, unpublished; Hlava

1974) (Figure 5), one sees clearly that the olivine in the dunite nodules is too Fe-rich to be from lherzolite inclusions, but that it falls well within the range for true dunite nodules and also overlaps with the most Fa-poor phenocrysts in basalts of Hawaii. Therefore, it is unlikely that the nodules are related to Hawaiian lherzolites but, on the basis of Fo content, could be related either to Hawaiian dunite nodules or phenocrysts of Hawaiian tholeiitic and alkalic basalts.

Contents of CaO, NiO, and MnO in olivine from the dunite nodules are compatible with those of olivine from true dunite inclusions of Hawaii and are unlike those from lherzolites and phenocrysts of tholeiitic and alkalic olivine basalts (Figure 6). This similarity between olivine in dunite nodules from basalts of Hawaii and those in the rhyodacite is further demonstrated by the composition of the clinopyroxene (Table 3; Figures 3, 7); i.e., the relatively low FeO and high Cr_2O_3 contents are characteristic for clinopyroxene from dunitic inclusions (see White 1966).

Spinel is too rich in FeO and too low in MgO and Al_2O_3 to be compatible with spinels in lherzolites of Hawaii (Kuno 1969) or with lherzolite spinel in general (see Aoki and Prinz 1974); nor is it compatible with spinel inclusions in olivine phenocrysts in some tholeiitic basalts of Kilauea volcano on the island of Hawaii (Evans and Wright 1972). On the other hand, they fall within the variation trend for the series chromite-titaniferous magnetite in both tholeiitic and alkalic basalts of Maui, Hawaii (Fodor, Keil, and Bunch, unpublished), as well as in mafic pegmatites of the Bushveld complex (Cameron and Glover 1973). Hence, the possibility of dunite nodules representing mantle material is unlikely.

It is suggested that dunite nodules in the rhyodacite are of the same type and origin as are dunite nodules found in alkalic basaltic rocks of Hawaii. According to White (1966), dunite nodules in Hawaiian volcanic rocks may simply be cumulates of early formed crystals from basaltic magmas. But the nodules in the rhyodacite have a "metamorphic" texture, which Jackson (1968) believes to be characteristic of a mantle regime; that is, recrystallized dunite nodules may represent residuum in the mantle left after melting to form tholeiitic magma. The forsterite content of the olivine in the nodules, however, is not high enough (e.g., > Fo_{88}) to represent residuum or true mantle material. Recrystallized textures can probably develop in the lower crust on the floor of magma chambers where early phenocrysts accumulate to form olivine-rich zones. It can be stated with certainty, however, that the dunite nodules are accidental inclusions, as indicated by the reaction relationship between the dunite and the host rhyodacite, where Fe-enrichment occurred in the olivine and amphibole formed at the margin.

Because olivine-rich zones are probably present in the crust beneath Hawaiian volcanic centers, as is indicated by gravity data for the Waianae volcanic center in which Kauaopuu Ridge lies (Strange, Machesky, and Woollard 1965), it is suggested that dunite nodules in the rhyodacite are accidental inclusions that were entrapped when the rhyodacite magma passed through the olivine-rich zones. The slightly metamorphic textures of the nodules may be the result of recrystallization at moderate depth under the Waianae volcanic center.

Source of the Megacrysts

Major and minor element contents in the olivine megacrysts (Figures 5, 6) show that they are most compatible with olivine in dunite nodules. However, the megacrysts are much larger than those in the dunite inclusions, and it is concluded, therefore, that the olivine megacrysts are not simply olivine crystals broken from the dunite nodules. On the other hand, their size is not unlike olivine grains in some olivine-rich rocks of the Hawaiian Islands, such as oceanites. The composition of chrome spinel in one megacryst is unlike the known compositions of spinel in lherzolites and basalts of Maui, Hawaiian Islands, but it is similar to those of tholeiitic basalts of Makaopuhi lava lake, Hawaii (Evans and Moore 1968). In contrast, the 2.4 wt.% TiO_2 in the spinel may indicate affinities with alkalic basalt (Sigurdsson and Schilling 1976).

The highly resorbed margins of the olivine

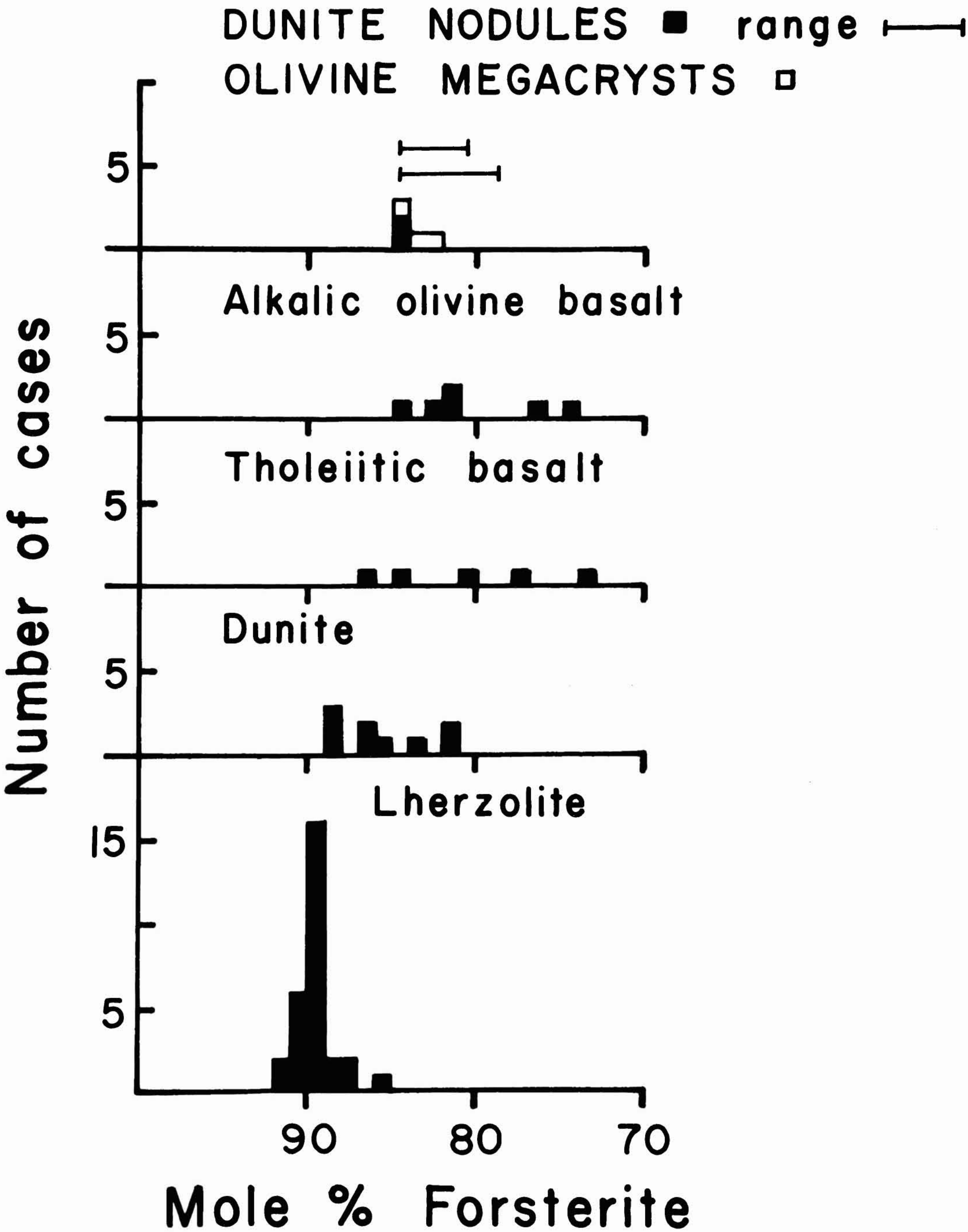

FIGURE 5. Histogram comparing compositions (mole percent forsterite) of olivine in dunite and olivine megacrysts (Kauaopuu Ridge, Oahu, Hawaiian Islands) to olivine in lherzolites and dunites of Hawaii (White 1966), and phenocrysts in basalts of Maui and Molokai, Hawaii (Fodor, Keil, and Bunch, unpublished; Hlava 1974).

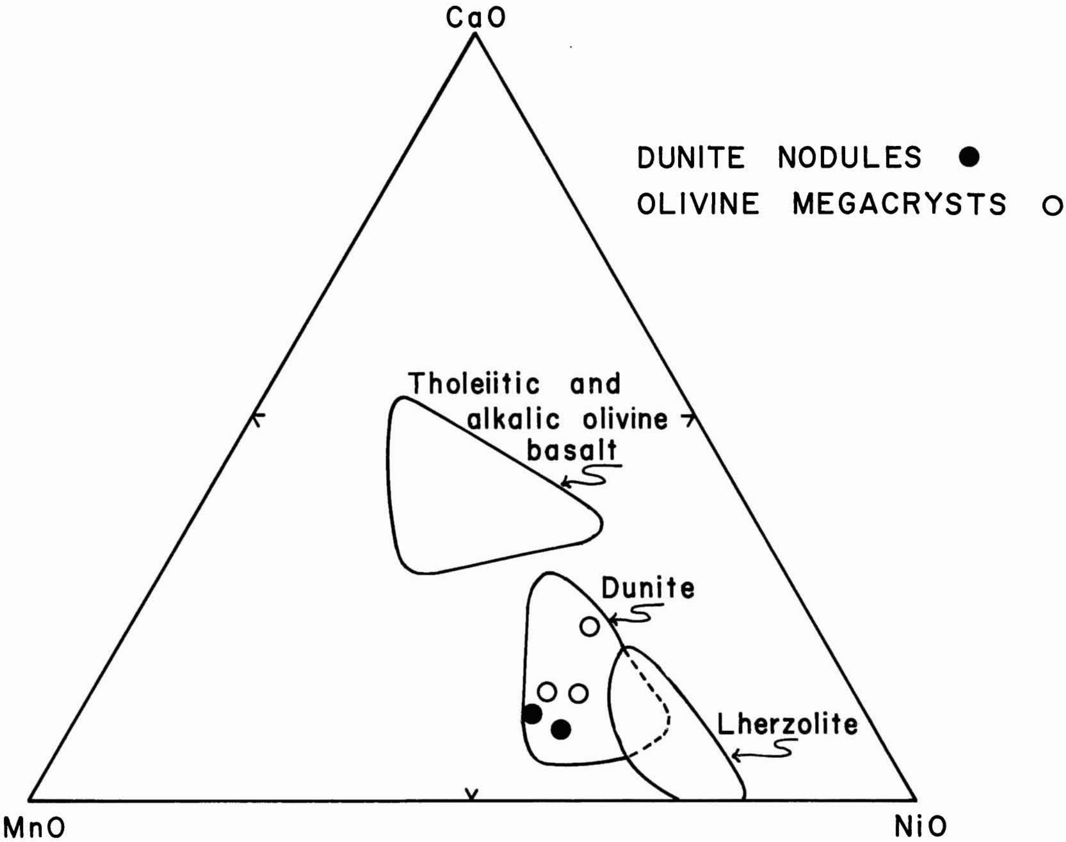

FIGURE 6. Comparison of CaO, NiO, and MnO contents in olivine from dunite inclusions and olivine megacrysts, Kauaopuu Ridge, Oahu, Hawaiian Islands, to compositional fields for olivine from lherzolites and dunites of Hawaii (White 1966), and olivine phenocrysts from basalts of Maui and Molokai, Hawaii (Fodor, Keil, and Bunch, unpublished; Hlava 1974).

are typical of what olivine phenocrysts experience during progressive crystallization of tholeiitic magmas. Possibly the olivine megacrysts were early phenocrysts in a basaltic precursor for the rhyodacite and escaped complete resorption during fractionation from basalt to rhyodacite. The absence of Fe-rich rims suggests that they did not react with the rhyodacite as the dunite nodules did but, instead, that they are probably genetically related to the rhyodacite by way of a basaltic precursor. The bulk compositions of two analyzed melt inclusions (Table 4) are intermediate between basaltic composition and the composition of the matrix glass of the rhyodacite (Bauer et al. 1973). It probably represents liquid trapped during fractionation of basalt to rhyodacite. This trapped liquid crystallized amphibole and orthopyroxene similar in composition to the amphibole and orthopyroxene crystallized from the rhyodacite host liquid, providing further evidence relating the megacrysts to the host rock.

Major-element contents in the clinopyroxene megacrysts (Figure 3) are compatible with those of dunite inclusions of Hawaiian volcanic rocks (White 1966), phenocrysts in alkalic olivine basalts of Maui and Molokai (Fodor, Keil, and Bunch 1975; Hlava 1974); and pyroxene inclusions in olivine phenocrysts in alkalic olivine basalts of Molokai, Hawaiian Islands (Hlava 1974). In contrast, the wollastonite content is slightly higher than that normally encountered in clinopyroxene

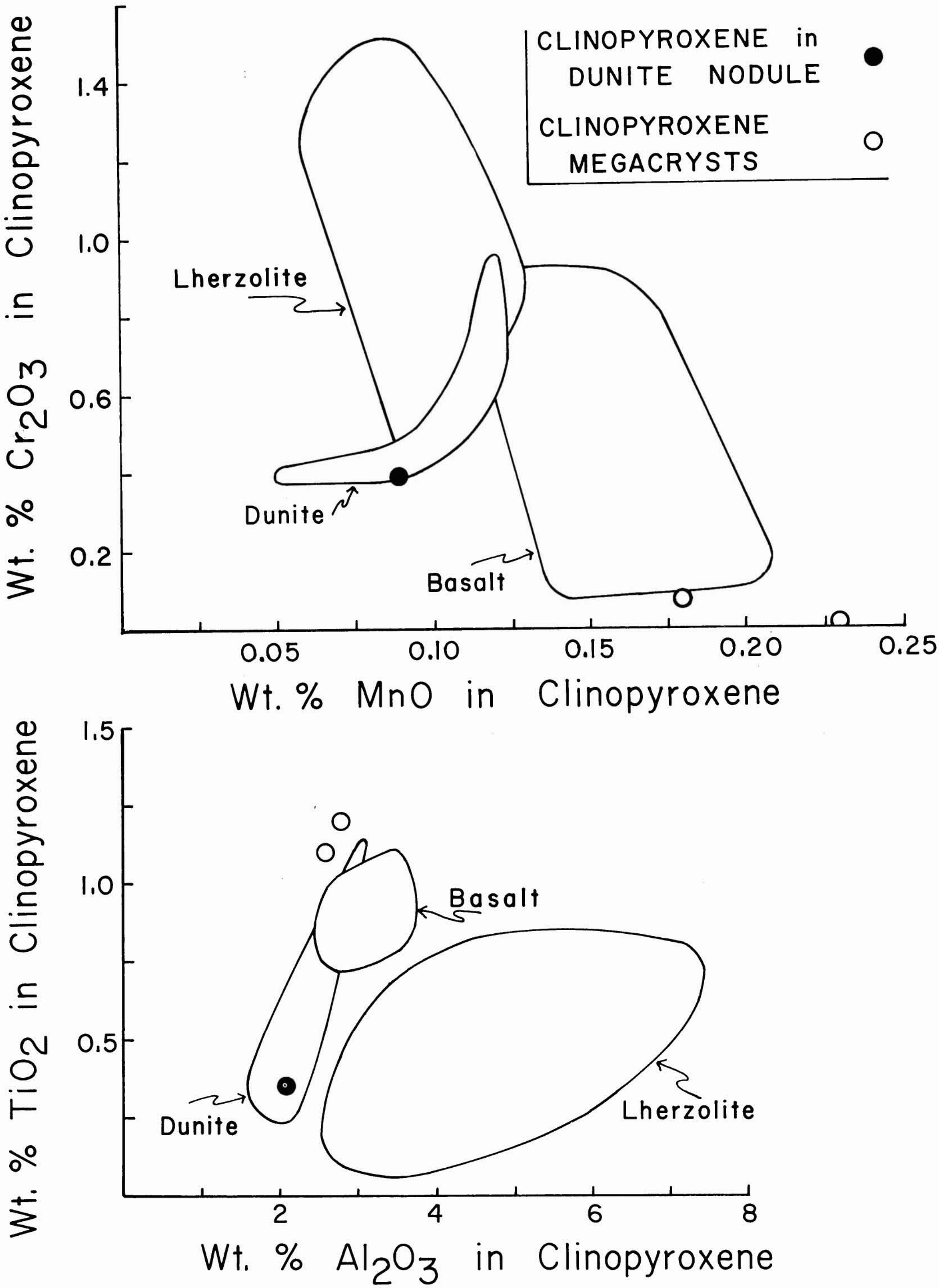

FIGURE 7. MnO and Cr_2O_3 contents and TiO_2 and Al_2O_3 contents in clinopyroxene in a dunite nodule and clinopyroxene megacrysts from the rhyodacite of Kauaopuu Ridge, Oahu, Hawaiian Islands, compared to compositional fields for clinopyroxene in lherzolites and dunites of Hawaiian Islands (White 1966), and phenocrysts in tholeiitic and alkalic basalts of Maui and Molokai, Hawaiian Islands (Fodor, Keil, and Bunch 1975; Hlava 1974).

phenocrysts from Hawaiian tholeiitic basalts; at best, Wo_{43} may indicate rocks transitional between tholeiitic and alkalic suites (Fodor, Keil, and Bunch 1975).

On the basis of minor elements, the clinopyroxene megacrysts are compatible with phenocrysts of either tholeiitic or alkalic olivine basalts of Hawaii (Figure 7). Conversely, the relatively low Al_2O_3 contents are unlike those of high-pressure ($\sim$ 10–20 kb) clinopyroxene megacrysts commonly present in alkalic basalts on a worldwide basis (e.g., Irving 1974, Whilshire and Shervais 1975). The clinopyroxene crystals, like the olivine megacrysts, may represent early phenocrysts formed in a precursor basaltic magma of the rhyodacite. Partial resorption of the megacrysts occurred as disequilibrium increased during progressive differentiation. The Mg-rich rim on the clinopyroxene probably resulted from crystallization after an increase in oxygen partial-pressures (e.g., Presnall 1966). At the time of formation of the Mg-rich rim, liquid close in composition to rhyodacite melt (Table 4) was trapped and is now present as melt inclusions between the Mg-rim and the major portion of the megacrysts (Figure 4). The compositions of the melt inclusions, then, indicate that the megacrysts were in a rhyodacitelike liquid at the time the Mg-rich rims formed. Subsequent crystallization produced orthopyroxene crystals in the zone adjacent one megacryst.

The affinities of the clinopyroxene megacrysts, as well as those of the chromite in olivine megacrysts, to basalts of *alkalic* lineage, as opposed to tholeiitic, present a problem. Up until now, the rhyodacites of Mauna Kuwale and Kauaopuu Ridge were considered to belong to the tholeiitic suite (Macdonald and Katsura 1964, Bauer et al. 1973). Possibly the apatite inclusions in the pyroxene megacrysts can shed additional light on this problem if it can be determined which type of basalt, alkalic or tholeiitic, is more likely to precipitate early apatite. The ferropseudobrookite in one pyroxene megacryst may provide a clue; this phase was previously reported in a fractionated tholeiitic lava of Kilauea on the Island of Hawaii (Anderson and Wright 1972).

According to our interpretation, the megacrysts in the rhyodacite support the hypothesis that the rhyodacite was derived from a basaltic magma by fractional crystallization. Furthermore, the occurrence of accidental dunite nodules rules out the likelihood of a rhyodacite origin by fractional crystallization in the upper crust. Probably the rhyodacite originated near the mantle-crust "interface" from the fractionation of a more mafic magma. During its ascent through the crust, the rhyodacite incorporated fragments of "metamorphic" dunite that had formed as a cumulate on the floor of a previous basaltic magma chamber.

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